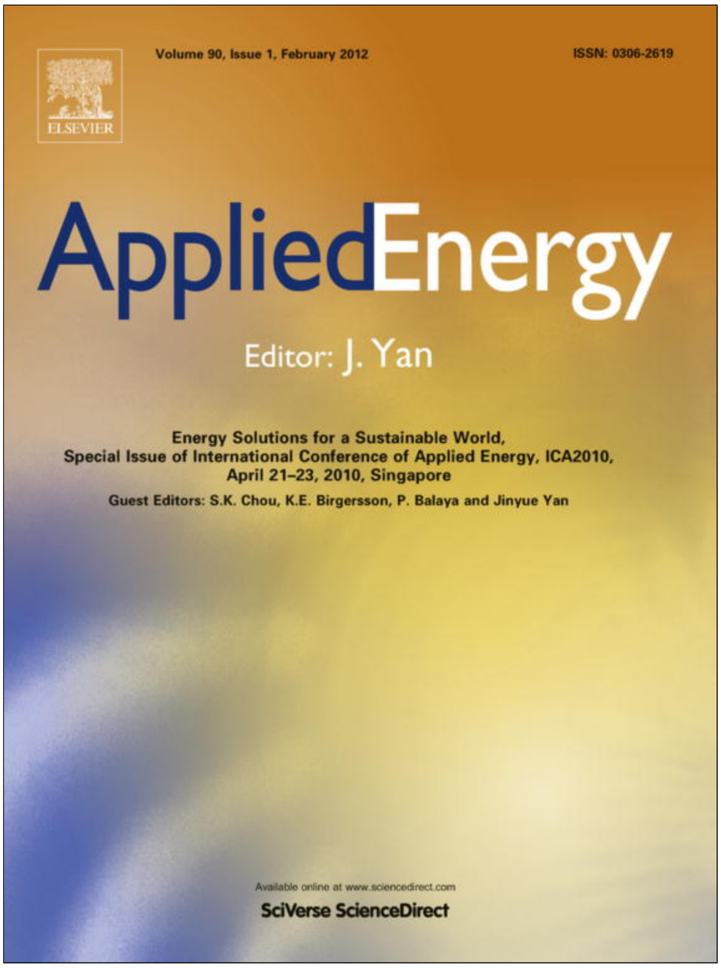
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An active cooling system for photovoltaic modules

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ABSTRACT

The electrical efficiency of photovoltaic (PV) cell is adversely affected by the significant increase of cell operating temperature during absorption of solar radiation. A hybrid photovoltaic/thermal (PV/T) solar system was designed, fabricated and experimentally investigated in this work. To actively cool the PV cells, a parallel array of ducts with inlet/outlet manifold designed for uniform airflow distribution was attached to the back of the PV panel. Experiments were performed with and without active cooling. A linear trend between the efficiency and temperature was found. Without active cooling, the temperature of the module was high and solar cells can only achieve an efficiency of 8–9%. However, when the module was operated under active cooling condition, the temperature dropped significantly leading to an increase in efficiency of solar cells to between 12% and 14%. A heat transfer simulation model was developed to compare to the actual temperature profile of PV module and good agreement between the simulation and experimental results is obtained.

1. Introduction

In recent years, renewable energy is widely advocated by many countries. PV cell is one of the most popular renewable energy products. It can directly convert the solar radiation into electricity which can be utilised to power household appliances. However, during the operation of the PV cell, only around 15% of solar radiation is converted to electricity with the rest converted to heat. The electrical efficiency will decrease when the operating temperature of the PV module increases.

Therefore, decreasing the temperature of PV module can boost the electrical efficiency. Generally, some techniques, like air cooling and water cooling, are utilised to cool the PV module to maintain lower operating temperature. Many numerical and experimental studies have been conducted to find out the most efficient and low cost hybrid PV/T system. Sometimes, the thermal energy extracted from the PV module can also be utilised for low temperature applications e.g. water and air heating.

In a number of studies, attention is focused on modifying the configuration of PV panel. By changing the structure of the panel, the variation of performance of the system can be observed. Dubey et al. [1] reported the efficiency of different configurations of PV/T-air collector. It was shown that the case of glass to glass PV with a cooling duct can give the highest efficiency among the four cases considered by the author. The annual average efficiency varied between 10.41% and 9.75% for the cases considered.

In order to enhance the heat transfer from the PV module, thereby effectively reducing the operating temperature and improving the efficiency of the PV module, Prasad and Saini [2] artificially increased the roughness of absorber plate and wall of the channel. However, increased roughness of wall and absorber incurred a pressure drop penalty and, therefore, required a higher pumping power. Han and Park [3] and Gupta et al. [4] showed that several types of ribs in the air channel can provide better performance for heat extraction but these are also accompanied by a significant increase in frictional losses. Garg and Datta [5] suggested several practical modifications to enhance the heat transfer in the air duct.

Garg et al. [6] presented a study of a PV/T air hybrid system, where the system included a plane booster and a flat plat collector mounted with PV module so that the effective absorption area of PV module can be significantly augmented. An optimization study of the absorber geometry for solar air heating collector was investigated by Pottler [7]. Naphon [8] carried out a study on the performance and entropy generation of the double pass solar air heater with longitudinal fins. This study showed that the thermal efficiency of PV module increases with increasing flow rate, as the heat transfer coefficient increases with increased Reynold number.

Tonui and Tripanagnostopoulos [9] also reported a study that an improvement of heat extraction can be achieved by low cost modifications of the channels of PV/T air system. Sopian et al. [10] presented a steady state simulation on single and double pass combined PV/T-air collector. The simulation results indicated that the double pass PV/T collector has superior performance during the operation. Joshi et al. [11] carried out an evaluation of a hybrid

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Nomenclature

A_c	aperture area of PV module (m^2)
c_p	specific heat capacity (J/kg k)
f	friction factor
$G(t)$	solar radiation (W/m^2)
h_c	heat transfer coefficient in air duct (W/m^2 k)
h_g	heat transfer coefficient of front glass (W/m^2 k)
I_{mp}	maximum power point current (A)
k	thermal conductivity (W/m K)
m	mass flow rate (kg/s)
p	packing factor
q_c	convective heat transfer
T_a	temperature of air flow (°C)
T_b	temperature of backsheet (°C)
T_c	cell temperature (°C)
T_g	front glass temperature (°C)
T_{in}	inlet temperature of air (°C)
T_{out}	outlet temperature of air (°C)
V_{mp}	maximum power point voltage (V)
Greek symbols	
σ	Stefan–Boltzmann constant (W/m^2 k^4)
ε_g	emittance of glass
α_T	Tedlar absorptivity
η_o	nominal efficiency of cell
α_c	cell absorptivity
τ_g	fraction transmitted through the front glass
η_e	cell efficiency
β	temperature coefficient (°C^{-1})
θ	panel tilted angle
v	kinematic viscosity (m^2 s^{-1})

PV/T system. Two types of PV module (glass to Tedlar and glass to glass) were utilised to investigate the performance under the meteorological conditions of New Delhi. The results showed that the overall performance of hybrid thermal collector with PV module glass-to-glass is better than glass-to-Tedlar.

In this study, the main focus is on the comparison of the electrical efficiency of the PV module with and without cooling. By varying the air flow rate through the duct, the electrical performance will also be investigated. In addition, a simulation model is developed to examine the actual temperature profile of Photovoltaic cell during operation.

2. Experiments

A test setup was designed to investigate the thermal and electrical performances of the PV/T air system. This system was installed on the roof top of EA building at the National University of Singapore. A schematic diagram of the complete experimental set-up is shown in Fig. 1.

This experimental set-up was designed to investigate how the temperature affects the efficiency and power output of PV panel during operation. Four 55 watt polycrystalline solar modules were used in the experiment to generate electricity. The electricity generated by the solar modules was stored in four deep cycle gel batteries. An array of air ducts that allowed air to pass through was attached underneath the PV modules. Fins were fitted in the duct to increase the heat transfer rate from the PV panel to the moving fluid. The inlet/outlet manifold was carefully designed to ensure uniform airflow distribution.

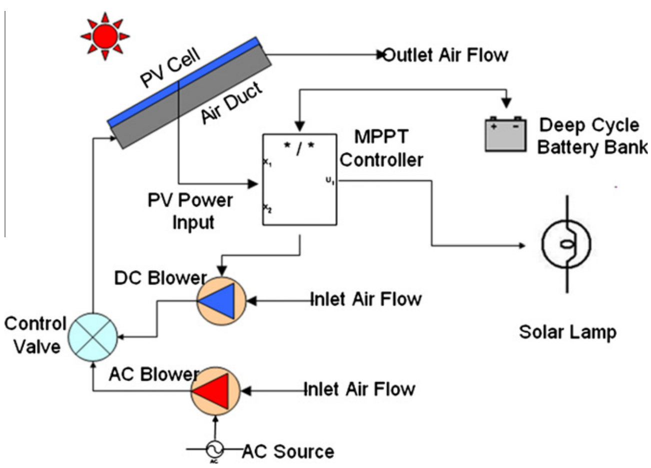

Fig. 1. A schematic diagram of the experimental set-up.

A direct current blower, which was connected to the batteries, extracted air from the surrounding to cool the modules. During the operation, a maximum power point tracker (MPPT) was used to modulate the power output from solar panel to ensure that the maximum electrical power is extracted. Another alternating current (AC) blower was also used in this experiment because it could function as variable speed blower, to control the flow rate passing through the duct. The experiments were conducted from 9:30 am to 5:00 pm. A pyranometer was used to capture the daily global solar irradiation. Temperature measurements are important in this experiment and therefore calibrated T-type thermocouples were utilised. In the experiment, PV current, PV voltage, temperature of panels, temperatures air at inlet and outlet manifolds, wind speed and solar irradiation were collected.

3. Mathematical formulation

The energy balance equations of the PV module are modified from Cox and Raghuraman [12]:

The total energy, E_c, absorbed by the PV cell is given by the following equation:

$$E_c = p\alpha_c\tau_g G(t) \tag{1}$$

Due to solar irradiation, the electrical energy, E_{ce}, produced by the PV cell is expressed by the following equation:

$$E_{ce} = \eta_e p\tau_g G(t) \tag{2}$$

and the thermal energy, E_{ct}, released by the PV cell is as follows:

$$E_{ct} = (1 - \eta_e/\alpha_c)p\alpha_c\tau_g G(t) \tag{3}$$

where p is the cell packing factor which is defined as the ratio of area of solar cell to the area of blank absorber; η_e is the cell efficiency represented as a function of the module temperature [13]

$$\eta_e = \eta_o[1 - \beta(T_c - T_o)] \tag{4}$$

where η_o is nominal electrical efficiency under standard condition given by

$$\eta_o = \frac{V_{mp}I_{mp}}{GA} \tag{5}$$

The rate of solar energy absorbed by Tedlar (material of back-sheet) after transmission from EVA (polymer encapsulant of solar cell) is

$$E_T = \tau_g(1-p)\alpha_T G(t) \tag{6}$$

Principle of energy conservation is applied to the components of the PV module as shown below:

$$(1-\eta_e/\alpha_c)p\alpha_c\tau_g G(t) + \tau_g G(t)\alpha_T(1-p) = E_{loss} + q_c \tag{7}$$

where E_{loss} is the energy losses from the front glass to environment through the forced and free convection, and radiation. The solar collector was exposed to the ambient so that the heat loss is transferred by the top glass cover to the surrounding due to the combination of free and forced convection. Free convection is due

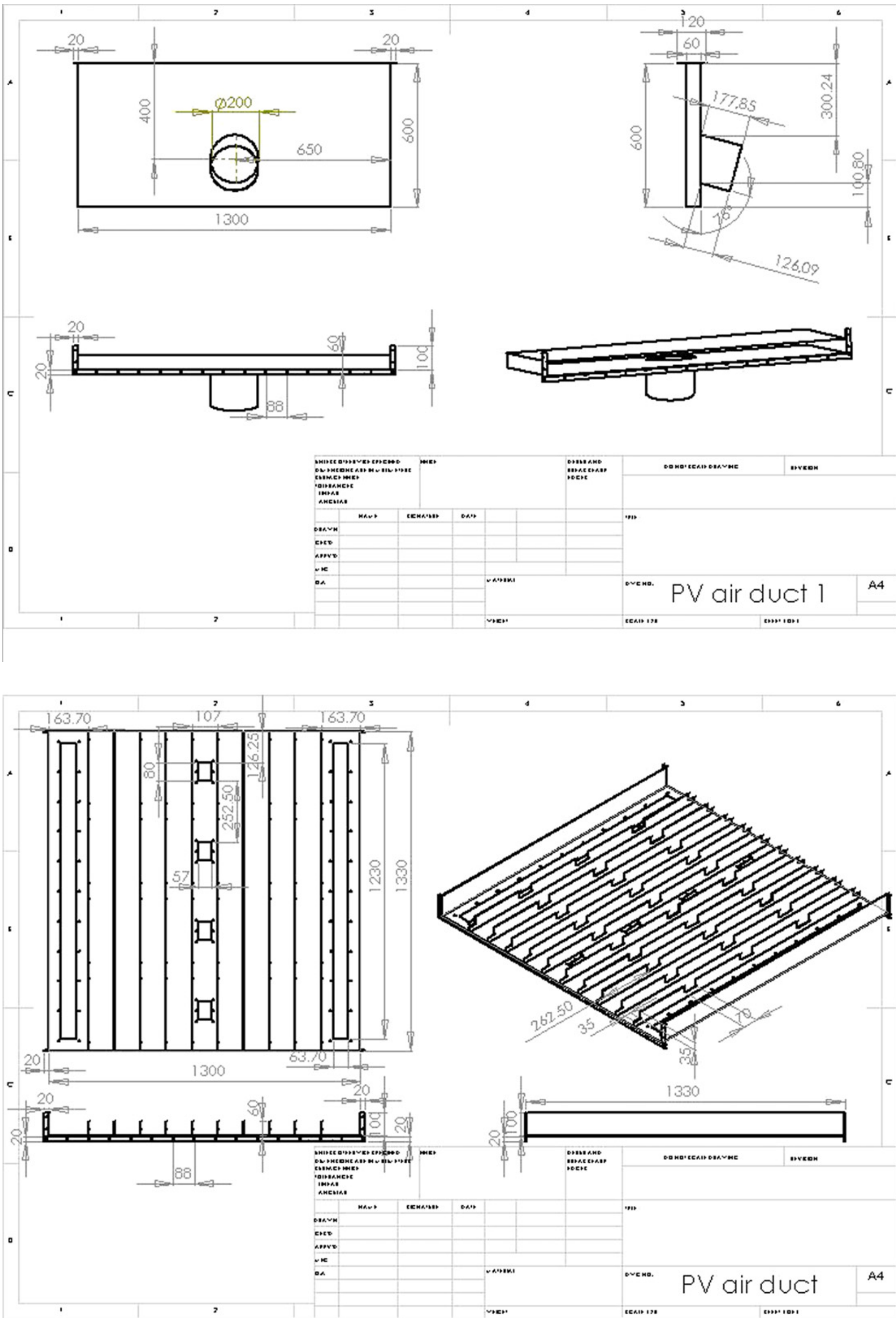

Fig. 2. Engineering sketch drawing.

to the air near the collector surface, which gets heated up producing the natural buoyancy force on the air. Forced convection is caused by the wind.

$$E_{loss} = h_g[T_g - T_a(t)] + \varepsilon_g \sigma T_g^4 - \alpha_g \sigma [T_a(t) - 6]^4 \quad (8)$$

and h_g is the forced convective heat transfer coefficient of the glass to the environment and an empirical correlation from Stultz and Wen [14] report is used

$$h_g = 1.247([T_g - T_a(t)]\cos\theta)^{1/3} + 2.658V \quad (9)$$

where T_g is the glass temperature, T_a is the ambient temperature, ε_g is the emittance of the glass, θ is the tilted angle of PV module, α_g is the absorptivity of glass and (T_a-6 °C) is assumed to be the sky temperature [15].

The convective heat transfer from the back of module can be presented by Newton's law of cooling:

$$q_c = h_c A_c [T_b - T_a(t)] \quad (10)$$

where h_c is given by [16]

$$h_c = \frac{k(f/8)U_m \mathrm{Pr}}{v[1.07 + 12.7(f/8)^{1/2}(\mathrm{Pr}^{2/3} - 1)]} \quad (11)$$

Pr is the Prandtl number, f is friction factor, U_m is average velocity of air, v is kinematic viscosity and k is thermal conductivity.

The energy balance of the air flow

$$\dot{m} C_p (T_{out} - T_{in}) = q_c \quad (12)$$

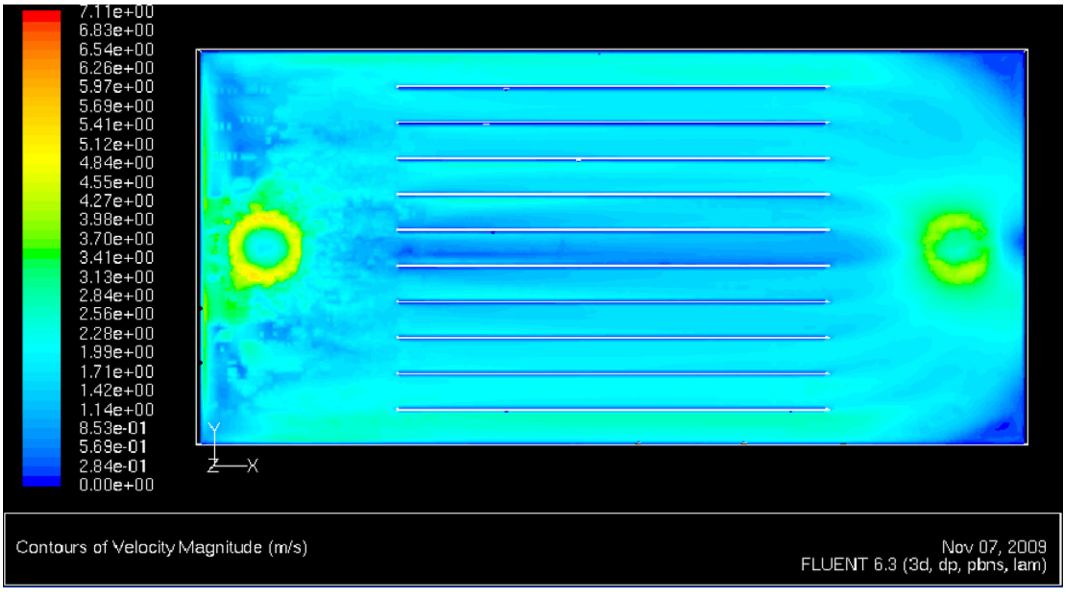

Fig. 3. Top view of velocity contour of manifold design.

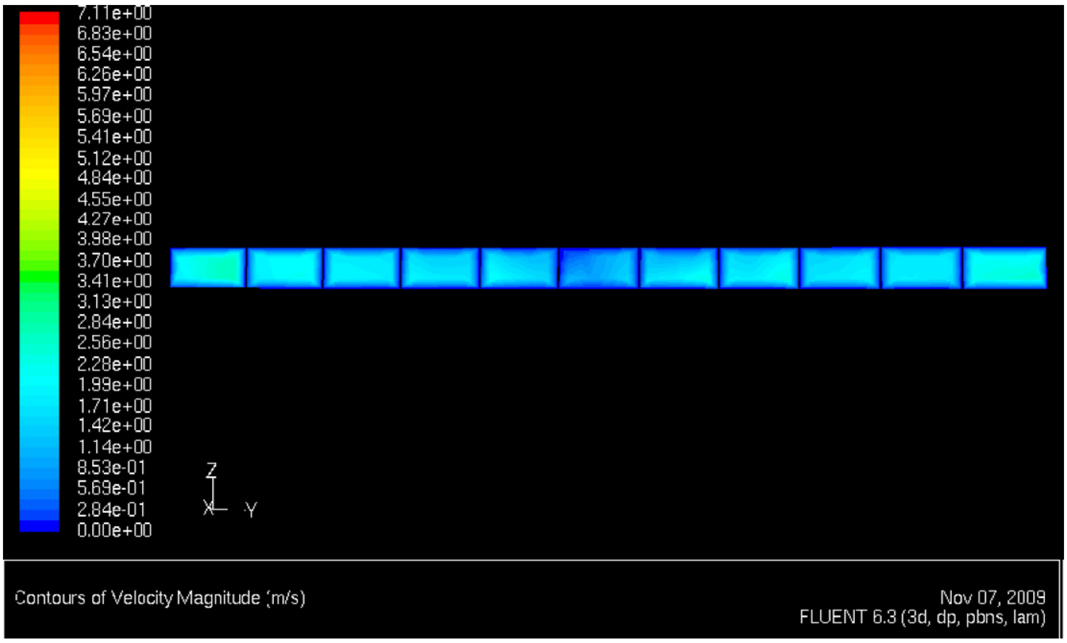

Fig. 4. Cross section view of velocity contour of manifold design.

The thermal efficiency can be computed with the following equation:

$$\eta_{th} = \frac{\dot{m}\, c_p \int (T_o - T_i)dt}{A_c \int G(t)dt} \tag{13}$$

The electrical efficiency of the PV module can be described as following equation:

$$\eta_e = \frac{\int VIdt}{A_c \int G(t)dt} \tag{14}$$

The total efficiency of the hybrid PV/T system is:

$$\eta_{total} = \eta_{th} + \eta_e == \frac{\dot{m}\, c_p \int (T_o - T_i)dt + \int VIdt}{A_c \int G(t)dt} \tag{15}$$

4. Results and discussion

To ensure that the flow is evenly distributed between the ducts, different manifold designs were modelled using a general computational fluid dynamics (CFD) package, FLUENT 6.3. The simulation result showed that the selected manifold design which is shown in Fig. 2, is capable of providing uniform flow distribution with no recirculation or significant dead volume as illustrated in Figs. 3 and 4. Such a manifold design will help reduce the temperature variation throughout the PV module during operation.

The electrical efficiency of the PV module is presented in Fig. 5. It can be observed that the electrical efficiency is a linear function of module temperature. The electrical efficiency of PV module declines with the increase in temperature of the PV module. During the experiment, cooling and non-cooling cases were considered. The impact of cooling is also shown in Fig. 5. Under the same meteorological condition, the temperature of non-cooling case is much higher than the cooling one resulting in lower electrical efficiency of the PV module.

The PV module temperature is linearly proportional to the irradiation and it is displayed in Fig. 6. With active cooling, the temperature of module increases 1.4 °C for every 100 W/m^2 increment of solar irradiation. However, if the PV module is not actively cooled, the increase of temperature will be higher at 1.8 °C for every 100 W/m^2.

Fig. 5 provides an indicative trend in the relation of electrical efficiency and operating temperature. A linear relation can be obtained:

$$\eta_{el} = 0.1577 - 0.0009T_{panel} \tag{16}$$

The theoretical efficiency of PV module can be obtained from Eq. (4). From the theoretical deduction, the electrical efficiency of the module can be written as the equation below:

$$\eta_{el} = 0.1664 - 0.0007T_{panel} \tag{17}$$

Based on the experimental data, Fig. 7 showed that the theoretical electrical efficiency is about 1–2% higher than experimental electrical efficiency. This discrepancy can be attributed to the module connection used in the current study which may result in a drop in the array electrical efficiency. The electrical efficiency from theoretical deduction is obtained under the conditions of single module. However, in this experiment, there are four PV modules connected both in series and parallel array. The different temperatures of the PV modules will result in variation in their electrical efficiencies thus compromising the overall system efficiency. The current result also compared reasonably well with the experimental result from Tonui and Tripanagnostopoulos [17], as shown below:

$$\eta_{el} = 0.147 - 0.0008T_{panel} \tag{18}$$

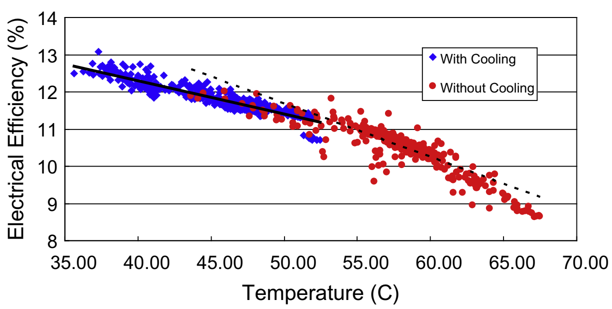

Fig. 5. Electrical efficiency as a function of PV temperature.

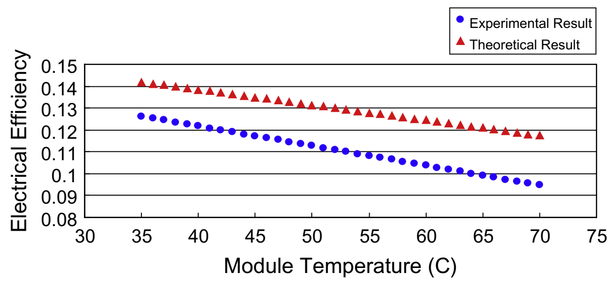

Fig. 7. A comparison between theoretical and experimental results.

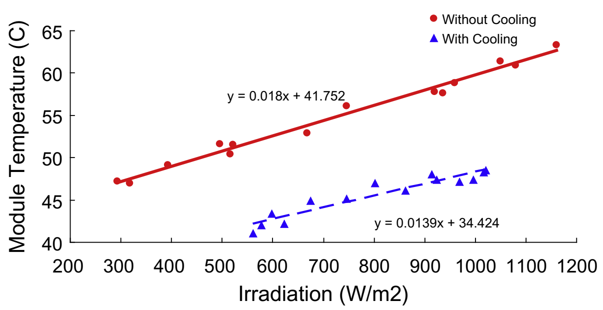

Fig. 6. Module temperature as a function of solar irradiation.

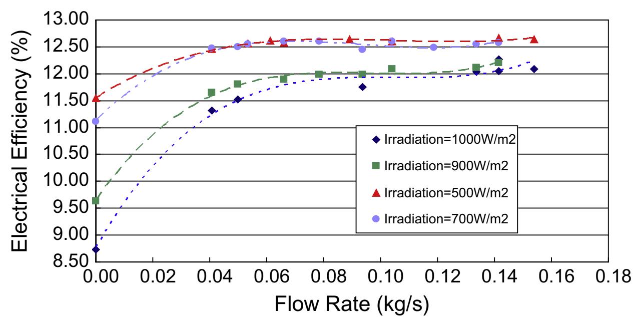

Fig. 8. Influence of flow rate on electrical efficiency.

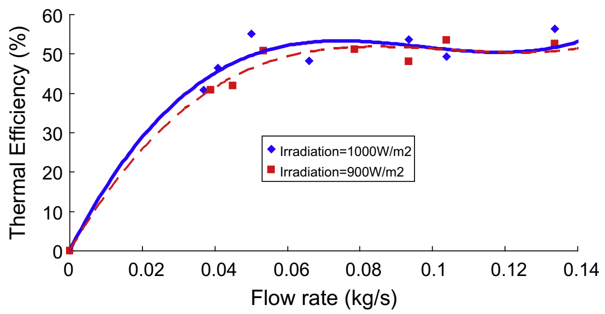

Fig. 9. Influence of flow rate on thermal efficiency.

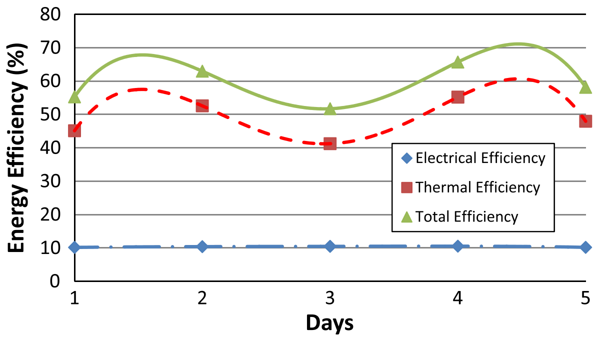

Fig. 10. A comparison of thermal and electrical efficiency over 5 days.

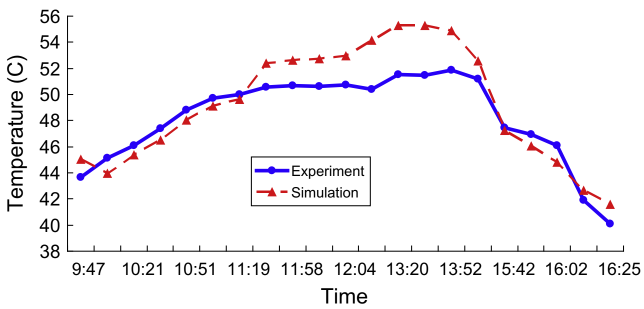

Fig. 11. A comparison of simulation and experiment in the temperature profile of the back of PV module.

The influence of flow rate on electrical efficiency is presented in Fig. 8. The electrical efficiency of the PV module increases with the flow rate until the flow rate reaches about 0.055 kg/s after which it maintains at a relatively constant value. This could be explained in association with the thermal efficiency of collector.

When the flow rate increases beyond 0.055 kg/s, the thermal efficiency of the collector will be maintained at a relatively constant level, as shown in Fig. 9. In other words, the heat extracted by the cooling fluid has reached a saturated level and it cannot be increased further by increasing the flow rate. Thus, the electrical efficiency of PV module will also be maintained at a relatively constant value beyond a flow rate of about 0.055 kg/s.

The efficiency of the system shown in Fig. 10 indicated that the electrical efficiency seems to be more stable than the thermal efficiency. The average electrical efficiency range is around 10.1–10.9%. However, the thermal efficiencies of the system are much higher than electrical efficiency of the system; it is about 40% higher. This showed that most of the solar irradiation is converted into heat and the thermal efficiency obtained from the experiment is significant compared to electrical efficiency. The total efficiency of the hybrid system is around 50–70%.

A heat transfer modelling/simulation was performed using a commercial finite element software-COMSOL MULTIPHYSICS. In this simulation, the meteorological data of 23 September 2009 were used to simulate the operation of PV system under the cooling condition. The purpose of this simulation is to investigate the temperature profile of PV module under the solar irradiation at 23 September 2009 and the experimental data are used to verify the simulation result. A good agreement between the simulation and experimental results has been shown in Fig. 11. Some deviations are shown from 12.00 pm to 2 pm. This may be attributed to the fact that the input insolation data of the simulation is based on a 2nd order polynomial curve fit of the actual measured data which did not fully capture the erratic fluctuations in actual insolation values from 12 pm to 2 pm.

Temperature profile of PV module is displayed in Fig. 12. The maximum temperature of the module occurs at the silicon cell. This is attributed to the high absorption of solar irradiation in silicon cell. Temperature of Tedlar (backsheet) is higher than front glass of PV module; this can be attributed to the closer location of the silicon cell compared to the front glass even though the thermal diffusivity of the glass is higher than Tedlar. In addition, the solar irradiation with the wavelength more than 1.1 μm will transmit the silicon solar cell and absorbed by the Tedlar. It is because that silicon cells are transparent to wavelengths longer than 1.1 μm and

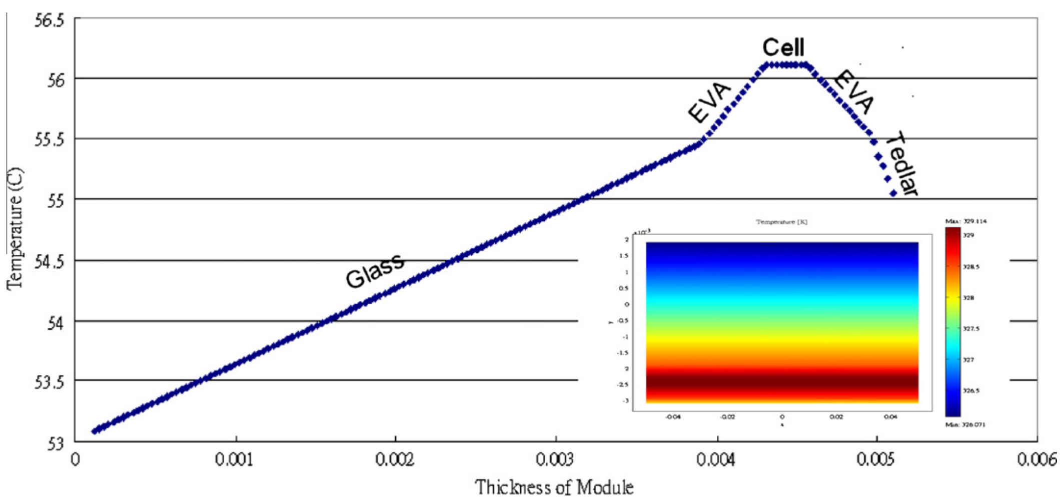

Fig. 12. Temperature profile of the PV cell at 1:30 pm (highest solar radiation on that day).

this wavelength corresponding to the band gap energy. Therefore, the simulation results show that the temperature at the back of PV module is higher than that of the front glass.

5. Conclusion

Both electrical and thermal energy are generated through the hybrid PV/T system. From the experiment result, it shows that the effect of using the active cooling mechanism. Under the situation where no cooling was used, the operating temperature of PV module attained a value as high as 68 °C and the electrical efficiency dropped significantly to 8.6%. By using the blower to cool the PV module, the operating temperature of module could be maintained at 38 °C and the electrical efficiency could also be kept at around 12.5%. Besides, an optimum flow rate was also found in this study. Air flow rate of 0.055 kg/s is sufficient to absorb the maximum amount of heat from the PV module. When the flow rate exceeds this value, the thermal and electrical energies are no longer affected. This helps in choosing the power rating of blower in order to avoid wasting unnecessary energy. Temperature gradient over the different PV module when connected together is also a key factor to affect the electrical performance. To boost the electrical efficiency of the PV module, temperature and temperature gradient over the PV module are considered critical. The increased efficiency of the air cooled PV/T systems will have a significant contribution to the applications of PV system.

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